Dissecting the di-jet asymmetry

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CERN

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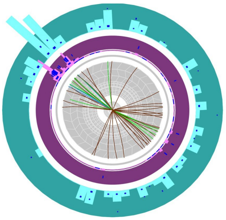
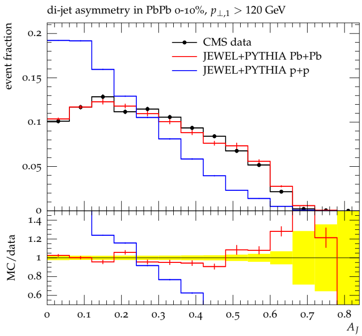
Introduction



tracks: $p_\perp > 2.6$ GeV

calorimeter cells: $E_\perp > 0.7/1$ GeV

ATLAS, Phys. Rev. Lett. **105** (2010) 024901



CMS, Phys. Lett. B **712** (2012) 176

$$A_J = \frac{p_{\perp 1} - p_{\perp 2}}{p_{\perp 1} + p_{\perp 2}}$$

- sizeable already in p+p
- significantly larger in Pb+Pb

Set-up for this study

Analysis cuts

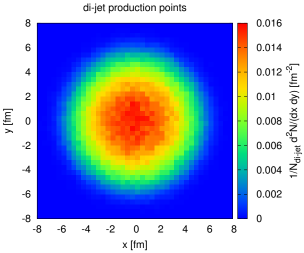
- anti-$k_\perp$ jets with $R = 0.4$
- $p_{\perp,1} > 100$ GeV, $p_{\perp,2} > 20$ GeV
- $\Delta\phi_{12} > \pi/2$

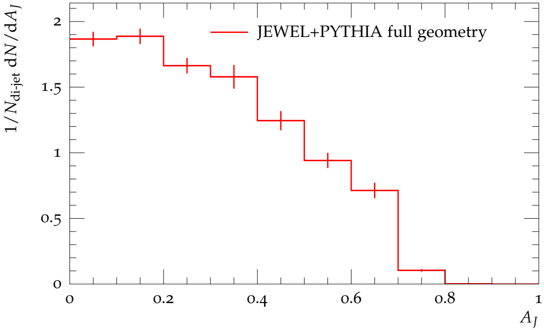
Simulation

- simulations done with JEWEL

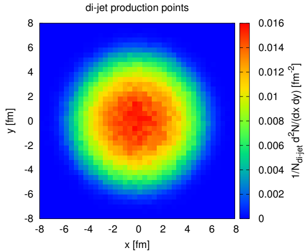
  arguments qualitatively more general
- standard (toy model) background
- $b = 0$

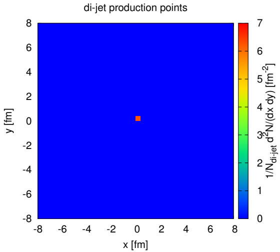
Importance of geometry

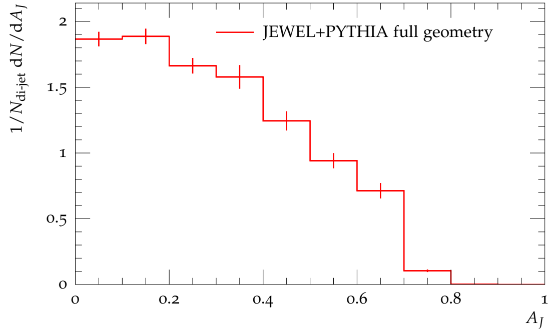




Importance of geometry







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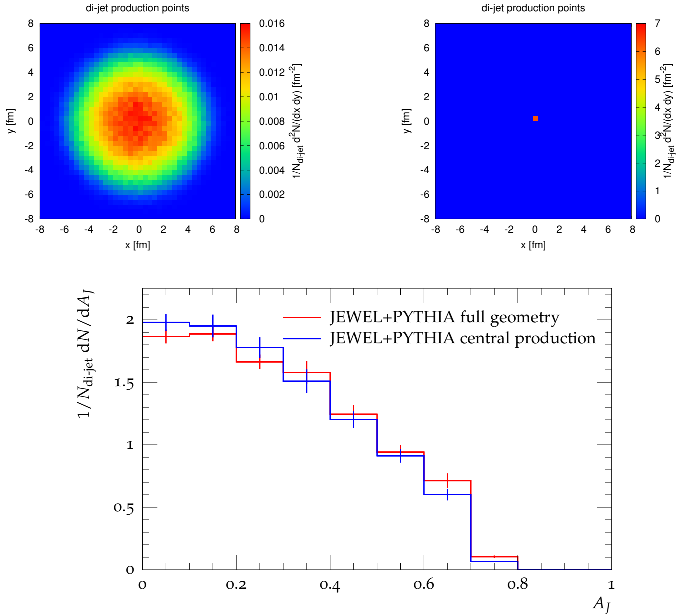
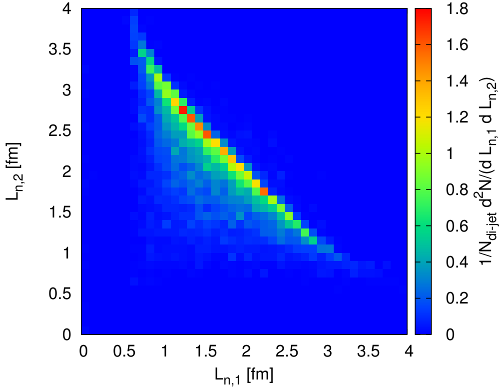
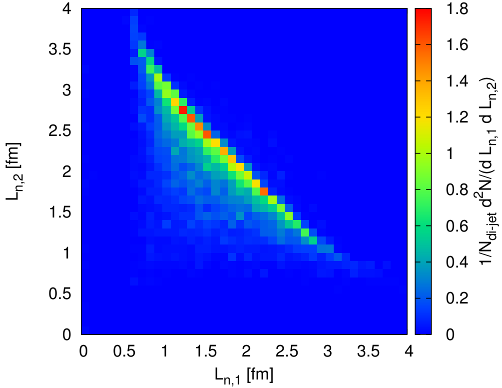


Path lengths



$$L_n = \frac{\int \mathrm{d}t\; t \cdot n(\mathbf{r}(t), t)}{\int \mathrm{d}t\; n(\mathbf{r}(t), t)}$$

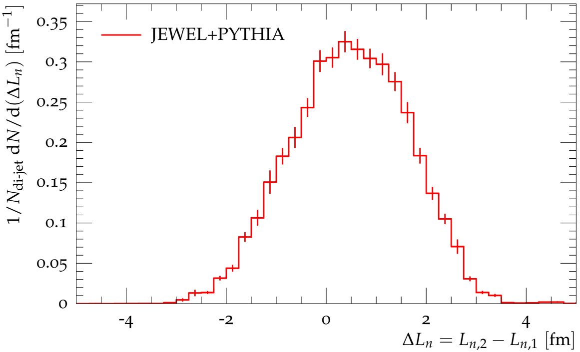
Path lengths



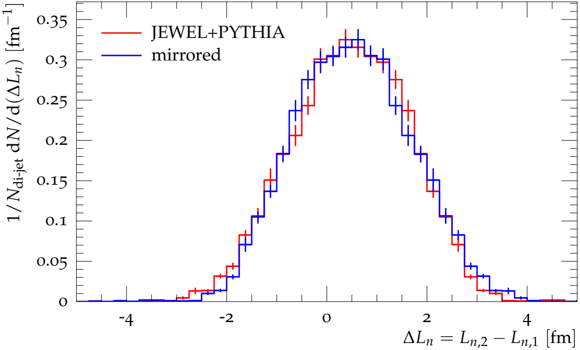
$$L_n = \frac{\int \mathrm{d}t\; t \cdot n(\mathbf{r}(t), t)}{\int \mathrm{d}t\; n(\mathbf{r}(t), t)}$$

- $\sim 35\,\%$ of di-jets have $L_{n,1} > L_{n,2}$

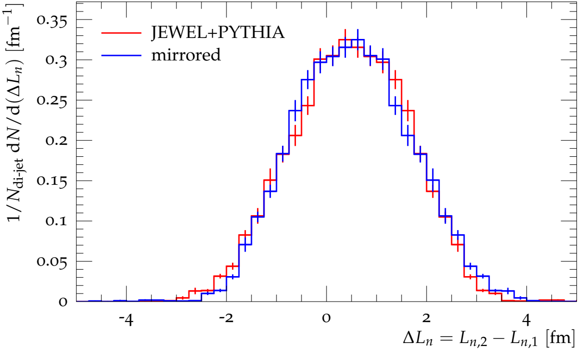
Path length differences



Path length differences

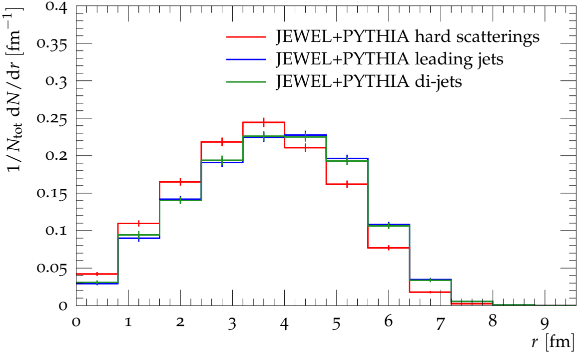


Path length differences

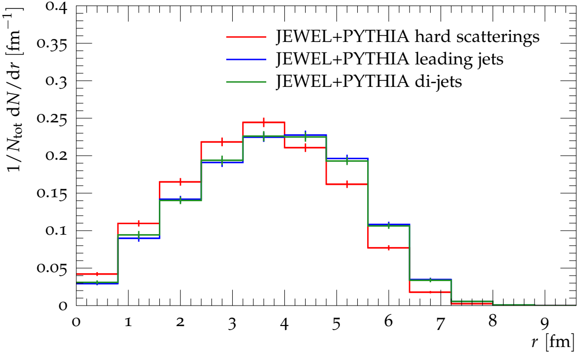


- $\langle L_{n,2} - L_{n,1} \rangle = 0.5\,\text{fm}$
- no preference for very asymmetric path lengths

Surface bias



Surface bias



- di-jet distribution resembles leading jet distribution
- no strong surface bias

Conclusions from geometric distributions

Conclusions from geometric distributions

- asymmetry increases in medium
- but geometry plays minor role

$\Rightarrow$ dominated by fluctuations

Sources of fluctuations

- fluctuations in vacuum fragmentation

give rise to asymmetry in p+p

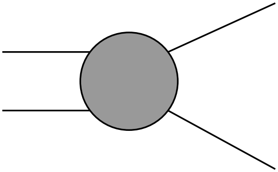
- fluctuations in energy loss

Contributions to di-jet asymmetry in p+p

- recoil from extra emissions
- jet reconstruction

Contributions to di-jet asymmetry in p+p

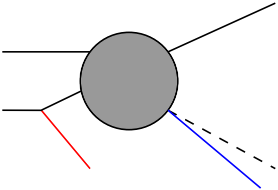
- recoil from extra emissions



- LO di-jet production — no asymmetry

Contributions to di-jet asymmetry in p+p

- recoil from extra emissions



- LO di-jet production — no asymmetry
- (first) emission from IS: one or both FS partons recoil — induces an asymmetry

Contributions to di-jet asymmetry in p+p

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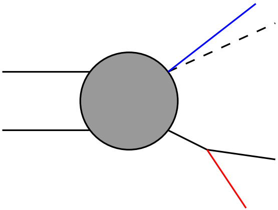

- LO di-jet production — no asymmetry
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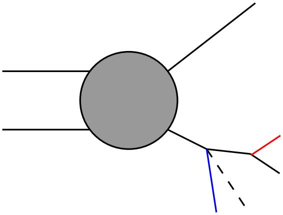
- emission from FS: other FS parton recoils — induces asymmetry (even when radiation ends up in same jet)

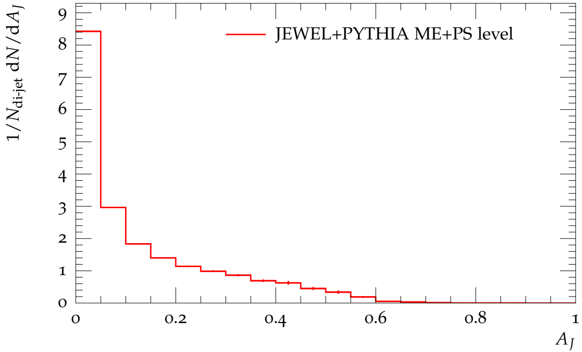
Contributions to di-jet asymmetry in p+p

- recoil from extra emissions



- LO di-jet production — no asymmetry
- (first) emission from IS: one or both FS partons recoil — induces an asymmetry
- emission from FS: other FS parton recoils — induces asymmetry (even when radiation ends up in same jet)
- further emissions from FS: recoil compensated 'locally' — no further increase of asymmetry

Asymmetry from recoil against emissions



- $2 \to 2$ scattering + recoil effects
- no jet reconstruction
- 'initial asymmetry'

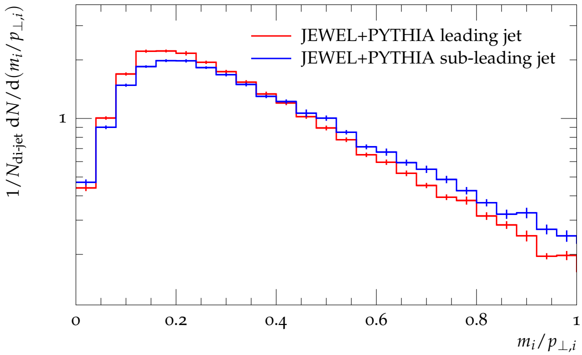
Contributions to di-jet asymmetry in p+p

- recoil from extra emissions
- jet reconstruction

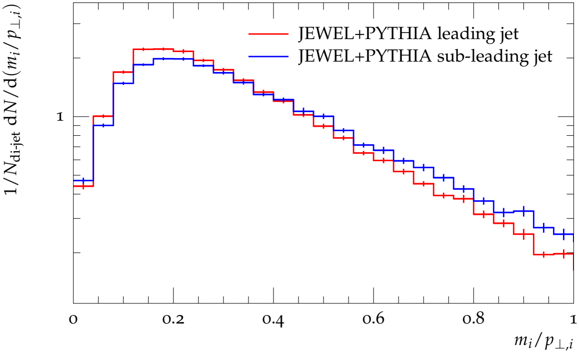
Contributions to di-jet asymmetry in p+p

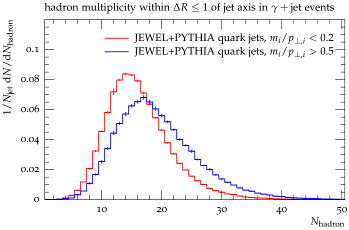
- recoil from extra emissions
- jet reconstruction
  - jet energy < parton energy due to incomplete reconstruction
  - multi-jet configurations
  - effects from hadronisation negligible
  - systematic element:
    - initially leading jet fragments harder than sub-leading
    - smaller $p_\perp$ loss due to jet clustering
  - fluctuations in jet fragmentation
  - $\sim 20\,\%$ probability for swap of initial ordering

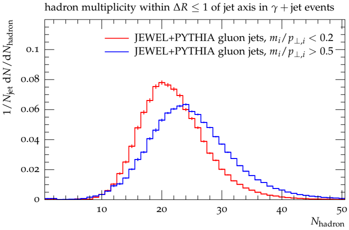
Leading/sub-leading jet fragmentation



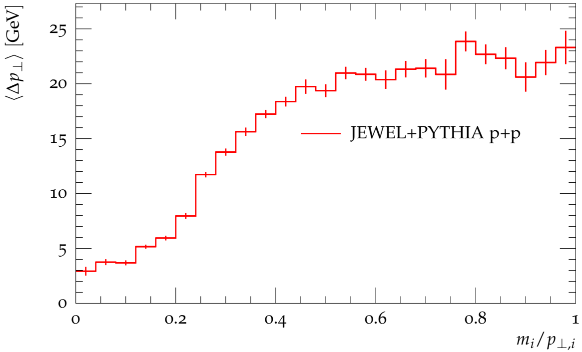
Leading/sub-leading jet fragmentation





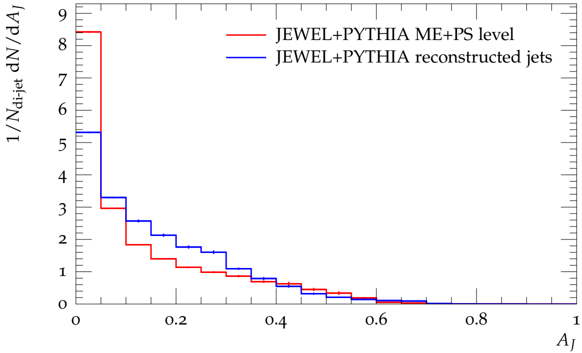


Average $p_\perp$ loss due to jet clustering

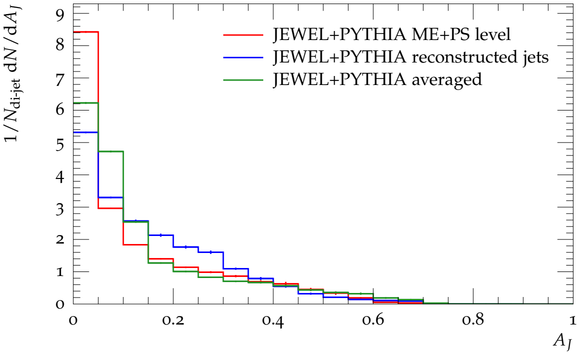


- caveat: requires matching initial partons to jets
- jets with harder fragmentation lose less $p_\perp$

Asymmetry due to jet reconstruction

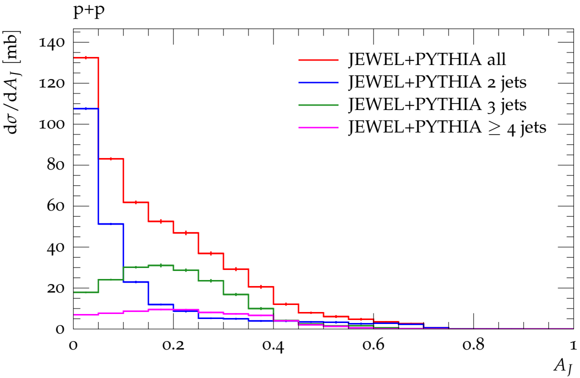


Asymmetry due to jet reconstruction



- initial partons + $\langle \Delta p_\perp \rangle (m_i / p_{\perp,i})$
- both systematic components & fluctuations important

Multi-jet configurations



- $p_\perp$ cut on all further jets same as for sub-leading jet

Energy loss in di-jets

General considerations

- medium interactions cannot perturb hard jet structures
- hard part of vacuum fragmentation pattern survives

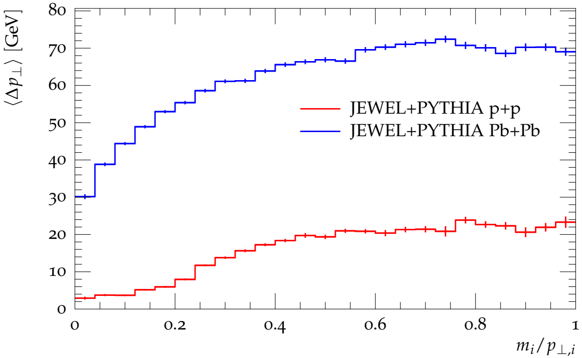
$\rightarrow$ initial asymmetry same as in p+p

- jets with harder fragmentation less susceptible to medium modifications & lose less energy

Contributions to asymmetry in A+A

- initial asymmetry
- fragmentation + energy loss + jet reconstruction
  - systematic component increasing initial asymmetry
  - fluctuations in jet fragmentation
  - fluctuations in energy loss
- geometry — small effect

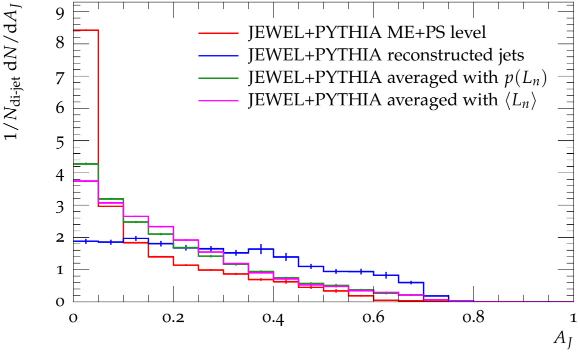
$p_\perp$ loss due to jet clustering and energy loss



- $p_\perp$ loss in medium also increases with $m_i/p_{\perp,i}$
- steeper than in p+p for $m_i/p_{\perp,i} \lesssim 0.3$

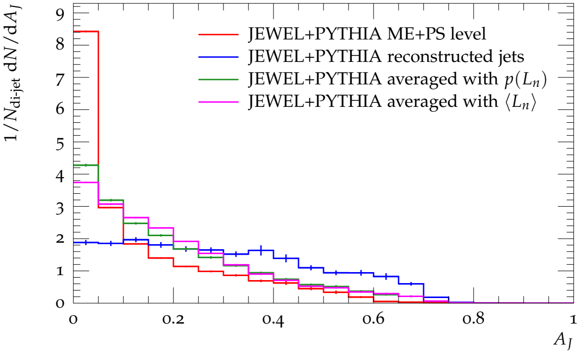
this is where the bulk of the distribution is

Asymmetry in A+A



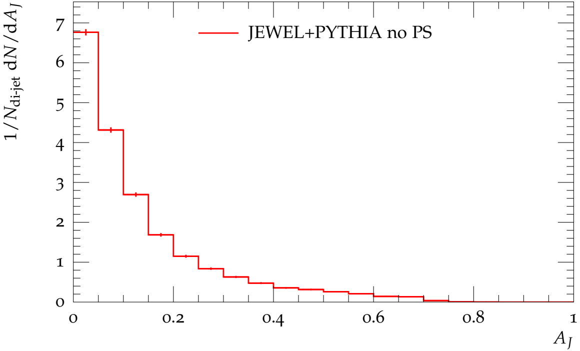
- green: initial partons + $\langle \Delta p_\perp \rangle (m_i/p_{\perp,i}, L_n)$
- magenta: initial partons + $\langle \Delta p_\perp \rangle (m_i/p_{\perp,i}, \langle L_n \rangle)$

Asymmetry in A+A



- probabilities for swapping jet ordering:
  - averaged $p_\perp$ loss: 29 %
  - full simulation: 35 % — was 19 % in p+p
- both systematic components & fluctuations important — as in p+p
- geometry plays only minor role

Asymmetry in A+A



- no parton showering → only 2 → 2 ME + energy loss
- di-jet production at $x = y = 0$
- energy loss fluctuations only source of asymmetry
- can contribute significantly to asymmetry
- cannot be compared quantitatively to scenario with PS

energy loss with & without PS very different

A comment on jet flavour

Expectations

- with parton-jet matching parton 'jet flavour' is known
- quarks fragment harder than gluons
- quark fraction in leading jets higher than in sub-leading
- medium effects increase quark fraction

  softer fragmentation $\rightarrow$ larger energy loss
- increase stronger in leading jets

  asymmetry increases in medium

A comment on jet flavour

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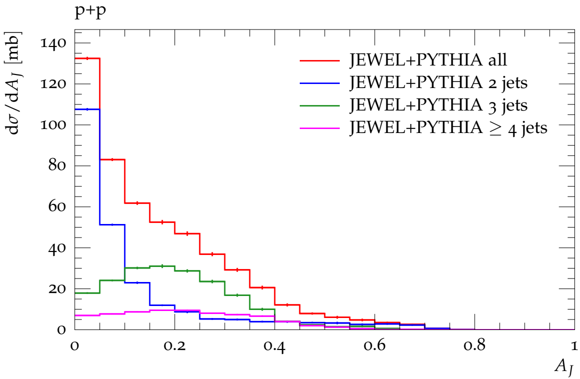
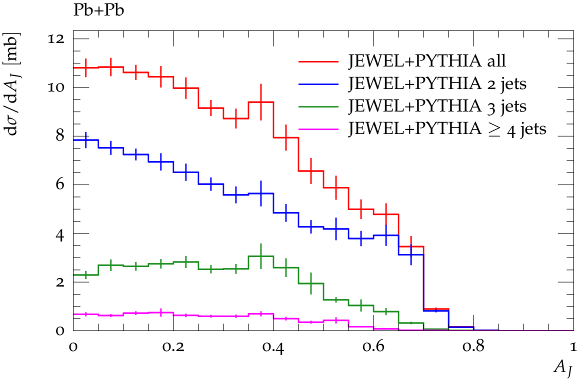
Quark fractions

	leading jet	sub-leading jet
p+p	54 %	47 %
Pb+Pb	68 %	52 %

Multi-jet contributions in medium



Multi-jet contributions in medium



Conclusions

- di-jet asymmetry dominated by fluctuations

  geometry unimportant

- in p+p: asymmetry due to fluctuations in fragmentation pattern
- in A+A:
  - enhancement of initial asymmetry
  - energy loss fluctuations
- medium induced energy loss depends on vacuum fragmentation pattern

  not only in di-jets, but generally